# THE TUNING ALGORITHMS USED BY THE DONNER 600 CRYSTAL TOMOGRAPH

W.W. Moses, S.E. Derenzo,
A.B. Geyer, R.H. Huesman, and D.C. Uber
Donner Laboratory and Lawrence Berkeley Laboratory,
University of California, Berkeley, CA 94720

## Abstract

We describe the computer algorithms used to adjust the energy thresholds and timing delays in the Donner 600 Crystal Tomograph. These thresholds and delays are adjusted using 1890 computer controlled digital to analog converters (DAC's) and a orbiting positron source. The energy threshold for each crystal is adjusted by measuring the counting rate of each crystal-crystal coincidence as a function of the DAC settings that control a pulse height window for the crystal in question. The DAC settings that correspond to the 511 keV photopeak are noted, thus determining the conversion from DAC setting to energy, and allowing the DAC's to be set to any desired energy window. The DAC settings controlling the timing delay for each channel are systematically adjusted to maximize the overall event rate. As these 1890 adjustments are coupled, we discuss the convergence of the tuning algorithms, and also report on the photomultiplier tube gain and timing variations over a period of 18 months.

## 1 Introduction

This paper describes the algorithms used to correct for the timing and gain variations among the 600 crystals and photomultiplier tubes in the Donner 600 Crystal Tomograph [1,2]. Photon pairs coming from a positron annihilation have two important characteristics that allow positron emission tomography (PET) systems to identify positron annihilations: each unscattered photon has a fixed energy (511 keV) and both photons enter the detector ring at the same time. However, crystal to crystal variations in response time make these photons appear to arrive at slightly different times and variations in the photomultiplier tube gain make the average photon energy appear to be something other than 511 keV. By correcting for these variations so that the relative timing and pulse height is the same for each crystal, the efficiency for detecting positron annihilations is increased and the observed number of false events is reduced.

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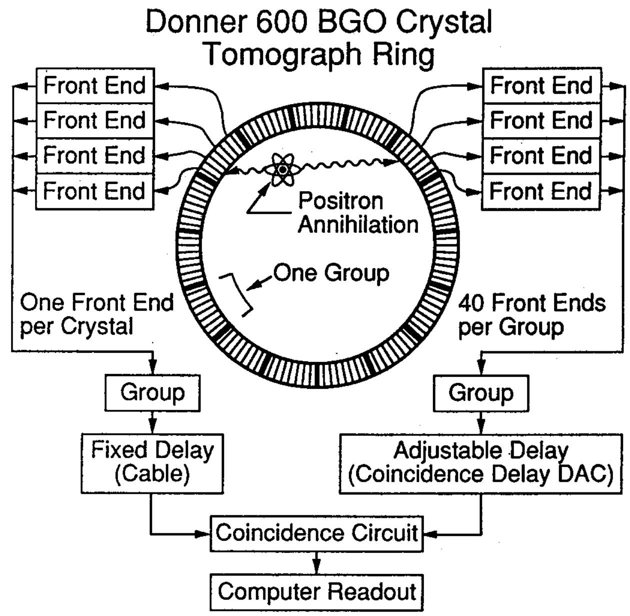


Figure 1: Conceptual Diagram of the Donner 600 Crystal Tomograph Electronics

This tomograph has 1890 computer controlled digital to analog converters (DAC's) that are used to make these adjustments. Each crystal in the tomograph is associated with two DAC's that control a pulse height window and one DAC that controls a timing delay, and each of the 45 group-group coincidence circuits (where a group consists of forty adjacent crystals) has two DAC's that control a coincidence timing delay and window width. The tuning is performed with the help of a 10 mCi $^{68}$Ge orbiting positron source [3,4], which provides each crystal-crystal combination with approximately five pairs of coincident photons per second.

The paper begins with brief description of electronics, followed by a description of the algorithms used to tune the pulse height and timing delay DAC's. We then demonstrate that these algorithms converge (i.e. are stable under repeated applications of the algorithm) and, in order to display the long term stability of the detector, present the gain and timing variations over a period of

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eighteen months of operation.

## 2 Electronics

Several tuning algorithms have been developed for the different types of DAC in the tomograph. A conceptual diagram of the electronics used by this tomograph [5,6] is shown in Figure 1. Each of the 600 crystals has an associated *front end* circuit that determines whether the signal seen by the crystal has the energy characteristic of positron annihilation, and provides a *front end timing* pulse when this characteristic energy is seen. Each front end circuit has three computer controlled DAC adjustments: an *Upper Pulse Height DAC*, a *Lower Pulse Height DAC*, and a *Front End Timing DAC*. The allowable range for each DAC is from 1 to 255 counts, with the approximate calibration for each DAC given in Table 1. Any photomultiplier tube signal with energy between the upper and lower energy thresholds will form a front end timing pulse, so the 511 keV positron annihilation energy can be selected by setting these two energy thresholds appropriately. This front end timing pulse is delayed by a length of time determined by the front end timing DAC.

Whenever any of the 600 front end circuits produces a timing pulse, a coincidence circuit determines whether any front end circuit on the opposite side of the tomograph ring has a simultaneous timing pulse. The number of coincidences that must be checked is dramatically reduced by combining the outputs of forty adjacent front end circuits to form a *group*, then determining when coincident pulses occur in opposing groups. To do this, an address circuit generates a *group timing pulse* whenever one (and only one) of its forty member crystals produces a front end timing pulse, and also records the identity of the crystal that caused the timing pulse. A *coincidence* circuit then looks at the group timing pulses from two address circuits, and if simultaneous pulses occur, sends the identities of the two crystals that detected the annihilation to a PDP-11/44 computer. There are fifteen groups in the Donner 600 Crystal Tomograph, and coincidences are made with the opposing six groups, so each address circuit is an input to six different coincidence circuits.

The 45 coincidence circuits (15 groups $\times$ six opposing groups $\times$ 1/2) each have two computer controlled adjustments that determine whether two group timing pulses are "simultaneous". The *Coincidence Delay DAC* is used to correct for overall group to group time differences due to different cable lengths, etc., while the *Coincidence Window Width DAC* determines how close the two group timing pulses must be in time in order to be called a coincident event. The approximate calibration for these DAC's are listed in Table 1. Since each coincidence circuit services only two groups, a single delay is sufficient to correct for the time difference between its member groups. Having only two groups per coincidence circuit also makes all 45 coincidence delay adjustments independent, which greatly simplifies the tuning procedure.

| Type of DAC | Approximate Calibration | Approximate Range |
|---|---|---|
| Upper Pulse Height | 4 keV/count | 0–1000 keV |
| Lower Pulse Height | 4 keV/count | 0–1000 keV |
| Front End Timing | 4 counts/ns | 65 ns |
| Coincidence Delay | 18 counts/ns | 15 ns |
| Coincidence Width | 35 counts/ns | 6.0–13.5 ns |

Table 1: DAC Calibration Factors

Finally, there are two computer generated *test pulses* that can be injected into each address circuit. These signals mimic front end timing pulses coming from real crystals, in that a group timing pulse is sent to the coincidence circuits whenever either of these signals occurs.

## 3 Tuning Algorithms

Of the five different types of DAC's listed in Section 2, four are adjusted with computerized tuning procedures [7]. The upper and lower pulse height DAC's are set with the *Pulse Height Tune*, while the front end timing and coincidence delay DAC's are set with a two step *Timing Tune*. The fifth type of DAC, the Coincidence Window Width DAC, is set to a fixed value, usually between 8 ns and 10 ns.

### 3.1 Pulse Height Tune

The goal of the pulse height tune is to set each pair of pulse height DAC's to bracket the positron annihilation energy (511 keV). However, the exact relationship between DAC counts and energy is not known initially. This relationship is obtained by using the orbiting positron source to illuminate all crystal-crystal combinations with 511 keV photon pairs. The pulse height thresholds for all crystals are held constant, except for a single test crystal, whose upper and lower pulse height DAC's are set so the crystal produces front end timing pulses only for a narrow energy range (typically 65 keV wide). The average energy (ie. the mean DAC setting) for this test crystal is varied, and the coincidence rate (summed over the opposing 160 crystals) is plotted as a function of this average energy. Four examples of this type of plot are shown in Figure 2(a). In each plot, the horizontal axis represents energy and the vertical axis represents the count rate.

Although the 511 keV photopeak is clearly seen in each channel, the presence of significant count rates at small energies (for example, channel 3 in Figure 2) makes it difficult to reliably determine the DAC value that corresponds 511 keV. Searching for the maximum count rate is sensitive to noise, and the low energy tail will bias a

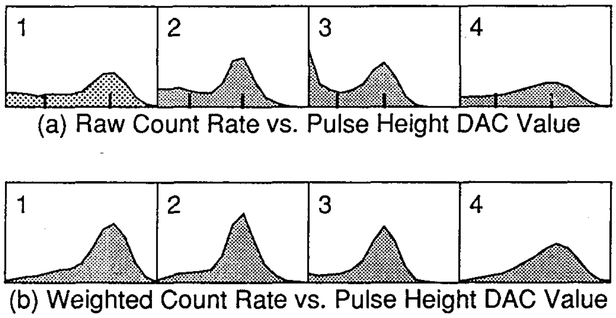


Figure 2: Plots Used by the Pulse Height Tune Algorithm

simple mean. Therefore, the position of the photopeak is computed with a weighted mean technique. The count rate at each DAC setting is multiplied by the DAC setting, which transforms the plots in Figure 2(a) into the plots in Figure 2(b). The center of gravity of the weighted count rates is computed, where the low energy tail is suppressed by ignoring those weighted count rates that are less than half of the maximum weighted count rate for that channel. This value is used as the 511 keV peak position, providing the conversion factor from energy to DAC counts for this crystal. Two tick-marks are shown in each plot in Figure 2(a). The right most mark in each plot corresponds to the position of the photopeak as determined by the weighted mean technique, while the left most mark corresponds to a resulting lower pulse height DAC setting of 200 keV.

In practice, 200 adjacent crystals are scanned simultaneously, as this is the maximum number that can be calibrated without interfering with the pulse height DAC's of the opposing crystals. Data is collected for 20 seconds at each pulse height setting, which corresponds to 15,000 coincident photon pairs per crystal. Note that this method assumes that the system is reasonably well tuned *before* the procedure starts, as it assumes that more coincidences will be obtained when the average energy is near 511 keV. If the pulse height thresholds of the opposing crystals or the timing is badly out of tune, there is no *a priori* reason to believe that the maximum coincidence rate will occur when the single crystal pulse height thresholds are properly set. However, experience has shown that this tuning procedure produces quite good results even when the rest of the system is badly out of tune. This tune typically takes about 40 minutes to perform.

## 3.2 Timing Tune

The algorithm for performing a timing tune is more complicated than the pulse height tuning algorithm due to the correlations between the various timing delays. The timing diagram for a properly tuned tomograph (ie. the state we attempt to achieve with the timing tune) is displayed in Figure 3. In this diagram, crystals 1 through 3 are members of the same group and crystals 301 through 303 are members of a different group. Suppose that these six crystals are excited simultaneously. The individual crystals and photomultiplier tubes have different (but constant) response times, so the photomultiplier tubes fire at different times. The first step of the timing tune is designed to adjust the front end timing DAC's so that all crystals within the same group produce simultaneous front end timing pulses. Therefore crystals 1 through 3 produce simultaneous front end timing pulses, as do crystals 301 through 303, but crystal 1 produces a front end timing pulse at a different time than crystal 301. One group in each coincidence circuit (the group containing crystals 301 through 303 in this example) has its group timing pulses delayed by a fixed time (set by the length of the cable connecting it to the coincidence circuit), while the other group in the coincidence circuit has its group timing pulses delayed by a computer adjustable amount (the coincidence delay). The second step of the timing tune adjusts the coincidence delay DAC so that the two group timing pulses are brought into time coincidence.

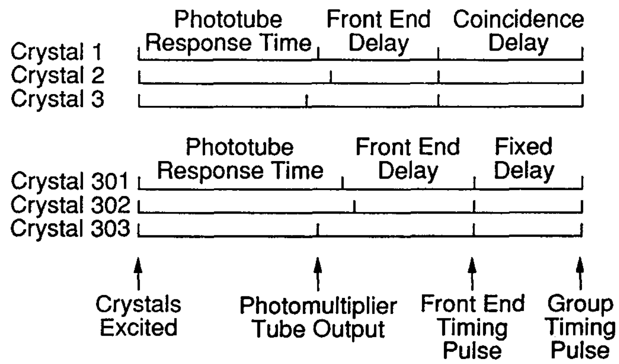


Figure 3: Coincidence Timing Diagram

The first step of the timing tune removes the crystal to crystal timing differences within one group with a procedure that is quite similar to the pulse height tune. The orbiting positron source provides pairs of coincident photons, and the front end timing DAC for a single test crystal is varied over its full range while the rest of the timing DAC's are held constant. The coincidence rate (summed over the opposing 160 crystals) is plotted as a function of the timing DAC setting; four examples of this plot are shown in Figure 4(a). In each plot, the horizontal axis represents delay time and the vertical axis represents the count rate.

The center of gravity of each peak seen in this plot is computed, plotted as the tick-mark in Figure 4(a), and used as the preliminary DAC setting. Since the purpose of this part of the timing tune is to remove the *relative* timing differences between crystals in a group, any *overall* shift (ie. shift in the group's average DAC setting) introduced by this process must be removed. Therefore, the group's average DAC value is computed before and after the tune, and the difference is subtracted from

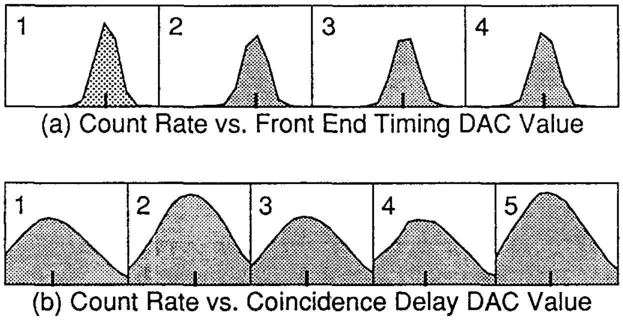


Figure 4: Plots Used by the Timing Tune Algorithms

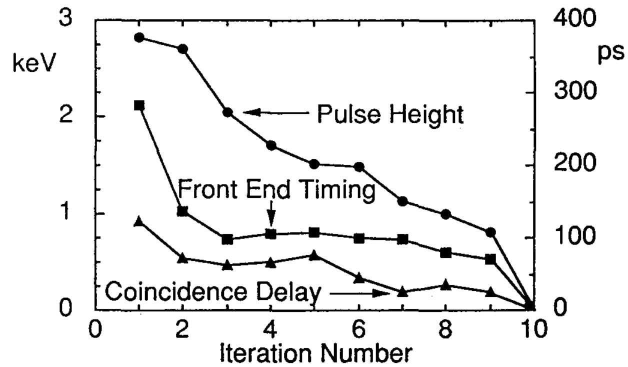


Figure 5: DAC Value Residuals vs. Tune Iteration

the preliminary DAC setting for each crystal within the group, thereby preserving the mean timing DAC value for the group. Like the pulse height tune, the first stage of the timing tune is actually performed on 200 adjacent crystals simultaneously, as this is the maximum number that can be calibrated without interfering with the timing DAC's of the opposing crystals.

The second part of the timing tune removes the group to group time differences after the crystal to crystal variations within each group have been removed. This is done by varying the coincidence delay DAC over its full range and plotting, as a function of DAC setting, the total coincidence rate between the two groups serviced by this coincidence circuit. Five examples of this type of plot are shown in Figure 4(b), where the horizontal axis represents delay time and the vertical axis represents the coincidence rate. Some difficulties arise selecting the optimal DAC setting because the full range of the coincidence delay DAC is only about 15 ns. Since the coincidence window width (typically 10 ns) is a large fraction of the delay range, the plots in Figure 4(b) have tails that extend beyond the physical limits of the coincidence delay DAC adjustment, and so a simple center of gravity computation will be biased. Therefore, the proper DAC setting is chosen by noting the count rate at the minimum and maximum DAC settings. The maximum of these two count rates is determined, and the center of gravity is computed using only those DAC settings with count rates above this value. In Figure 4(b), the central tick-mark in each plot represents the DAC setting computed using this method.

As all 45 group-group coincidences are completely independent, all 45 coincidence delay DAC's are tuned simultaneously. Finally, because test pulse signals mimic properly tuned front end channels, it is possible to perform the second step of the timing tune using only these "crystals". This is usually done only if the system is very badly out of tune – coincidences from real positron annihilations are preferred for tuning.

Like the pulse height tune, the timing tune algorithms assume that the system is reasonably well tuned before the procedure starts, as they assume that more coincidences will be obtained when the timing DAC's are adjusted properly, even if the rest of the system is poorly tuned. In addition, the 7 ns full range of the coincidence delay DAC's is much smaller than the 64 ns full range of the front end timing DAC's, and so improper front end settings can cause the optimal group delay setting to be outside of its physical range. However, experience has shown that this tune is also robust as long as the optimal coincidence delay DAC setting is within its physical range. This pair of tunes typically takes about 40 minutes to perform.

# 4 Convergence

In order to show that the algorithms described in Section 3 algorithms converge, that is, that the results it gives approach a constant value after repeated applications of the algorithm, the tomograph is tuned as if it is being turned on for the first time. All front end timing DAC's are set to their mid-range value (128 counts), and the lower and upper pulse height DAC's are set to make the pulse height window as wide as is practical (15 and 255 counts respectively). A series of ten pulse height and timing tunes are performed, and each DAC value is recorded as a function of iteration number. For each DAC, the residual versus iteration number is computed, where the residual is defined as the difference in DAC values between this iteration and the final iteration. For each species of DAC, the mean of the absolute value of the residuals is computed and plotted as a function of iteration number in Figure 5.

The mean absolute residual for the pulse height, front end timing, and coincidence delay DAC's are all less than one DAC count (Table 1) after the second iteration. They never reach zero (except at iteration 10, which is zero by definition) due to random fluctuations of one least DAC count. The fact that these residuals approach zero quickly implies that the tuning algorithms converge quickly, while the fact that they remain small implies that the tuning algorithms do not cause the DAC settings to drift or walk.

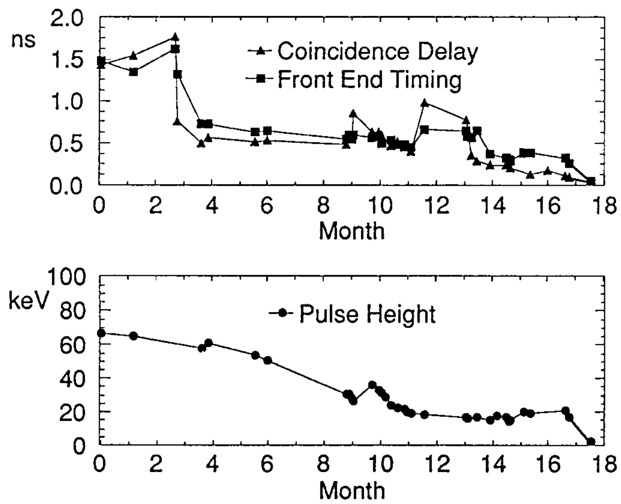


Figure 6: DAC Value Residuals vs. Time

# 5 Long Term Stability

The long term stability is analyzed by collecting the DAC values resulting from approximately 50 tunes performed over a period of 18 months. These DAC values are analyzed using the same method described in Section 4, with the residual defined as the difference from the final DAC value. The results, plotted in Figure 6, show that the front end timing and coincidence delay DAC's are quite stable over time, with a typical variation less than 0.75 nanoseconds over a year and a half of operation. The mean absolute residual of the pulse height DAC values varies significantly during this time due to long term changes in photomultiplier tube gain. However, this change in gain is slow (25% per year), and the pulse height tune is easily able to compensate for it.

# 6 Conclusions

In conclusion, we have described relatively simple algorithms for adjusting the 1890 DAC's that control the energy thresholds and timing delays in the Donner 600 Crystal Tomograph. Using a 10 mCi $^{68}$Ge orbiting positron source, the timing and energy threshold tuning algorithms each take approximately forty minutes to perform, which allows the tomograph to be tuned on the same day that a study is performed. These algorithms converge to less than a least DAC count in a few iterations, and the tomograph system is stable (modulo photomultiplier tube gain variations) over a period of 18 months.

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